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(54) **HEART SOUND TRACKING SYSTEM AND METHOD**

(71) Applicant: **Cardiac Pacemakers, Inc.**, St. Paul, MN (US)

(72) Inventors: **Abhilash Patangay**, Inver Grove Heights, MN (US); **Krzysztof Z. Siejko**, Maple Grove, MN (US); **Gerrard M. Carlson**, Houston, TX (US)

(73) Assignee: **Cardiac Pacemakers, Inc.**, St. Paul, MN (US)

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(58) **Field of Classification Search**
USPC 600/513, 528, 529; 607/17
See application file for complete search history.

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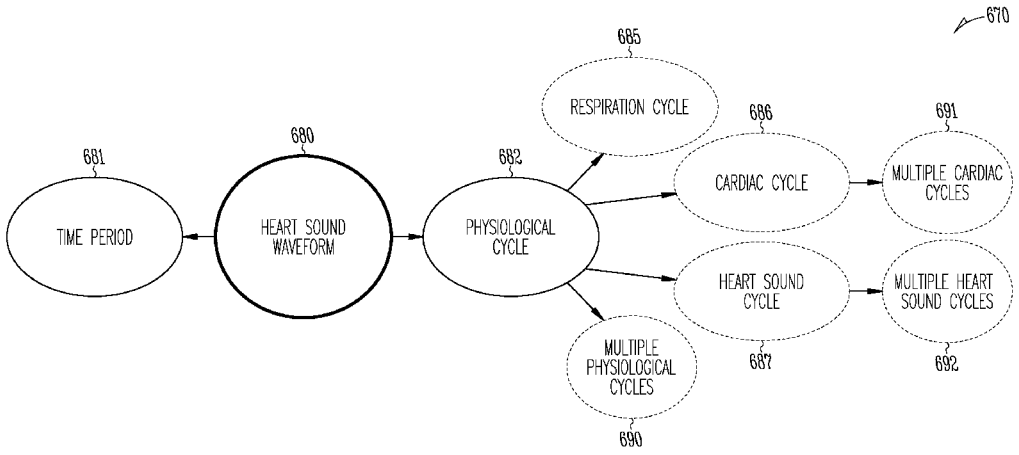
Primary Examiner — Carl H Layno
Assistant Examiner — Jon Eric C Morales
(74) *Attorney, Agent, or Firm* — Schwegman Lundberg & Woessner, P.A.

(57) **ABSTRACT**

A system and method provide heart sound tracking, including an input circuit, configured to receive heart sound information, and a heart sound recognition circuit. The heart sound recognition circuit can be coupled to the input circuit and can be configured to recognize, within a particular heart sound of a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform. The particular heart sound can include at least a portion of one of S1, S2, S3, and S4. Further, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can correspond to the at least a portion of one of S1, S2, S3, and S4, respectively.

6 Claims, 8 Drawing Sheets



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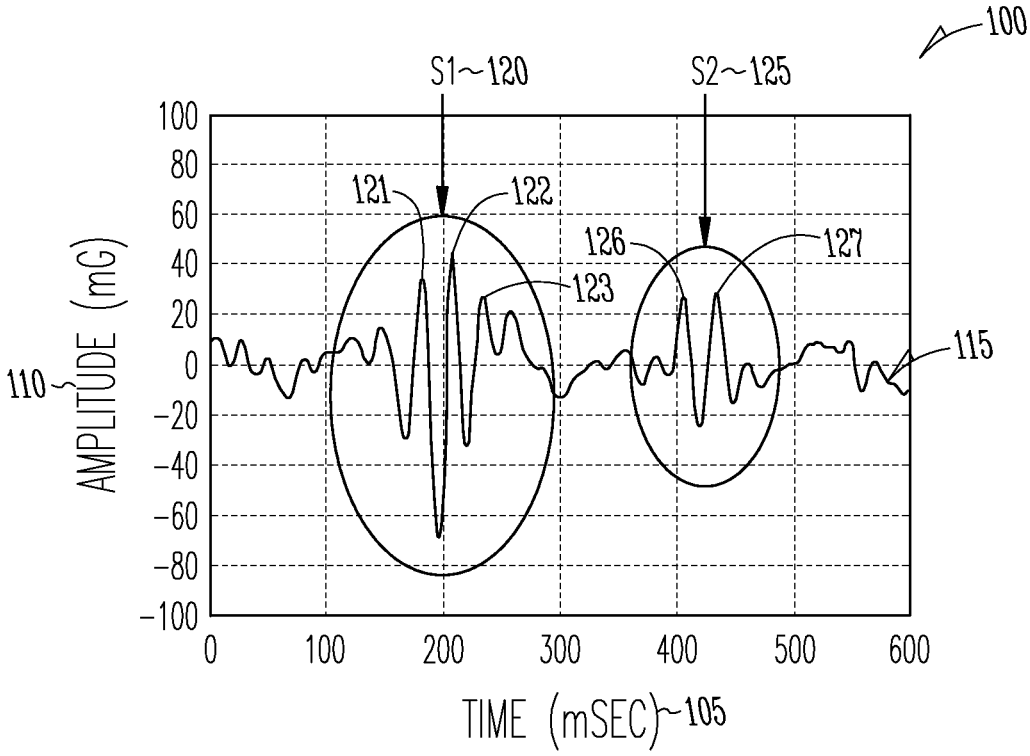
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−80
−100
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400
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600
TIME (mSEC)~105

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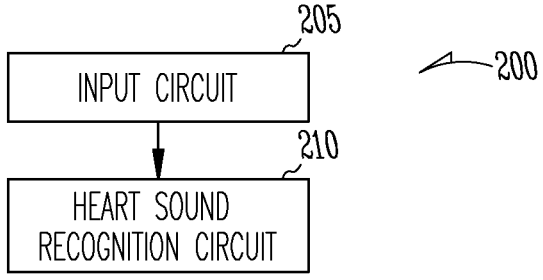
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210
HEART SOUND
RECOGNITION CIRCUIT

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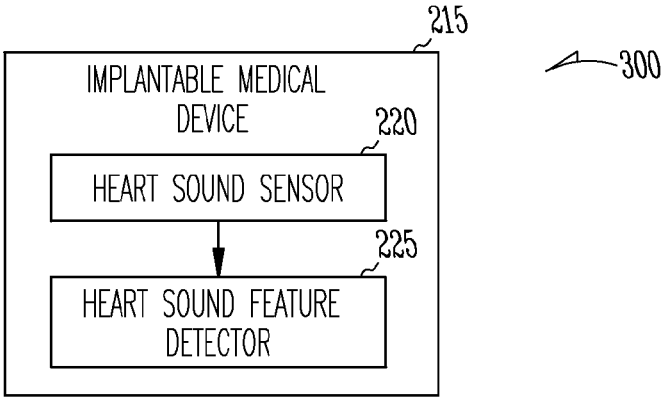

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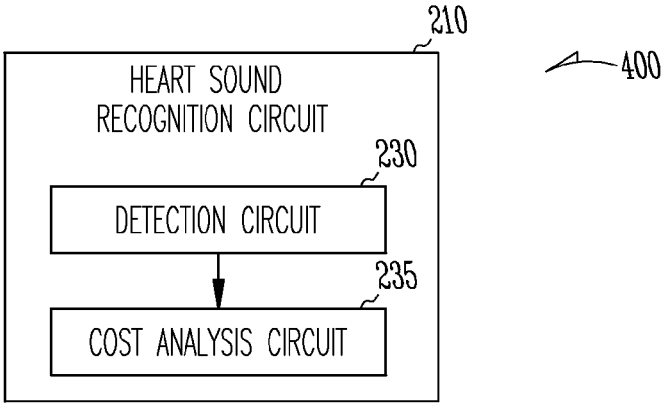

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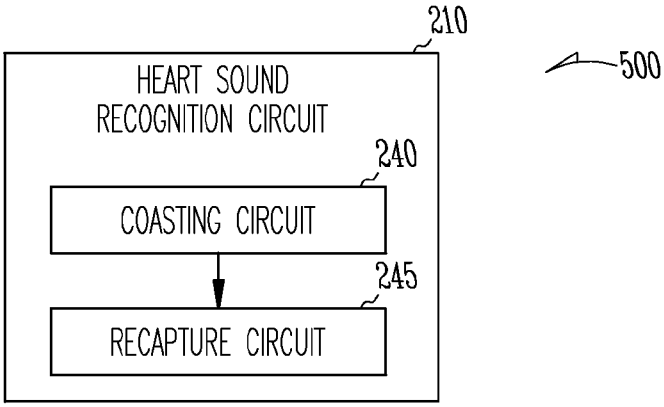

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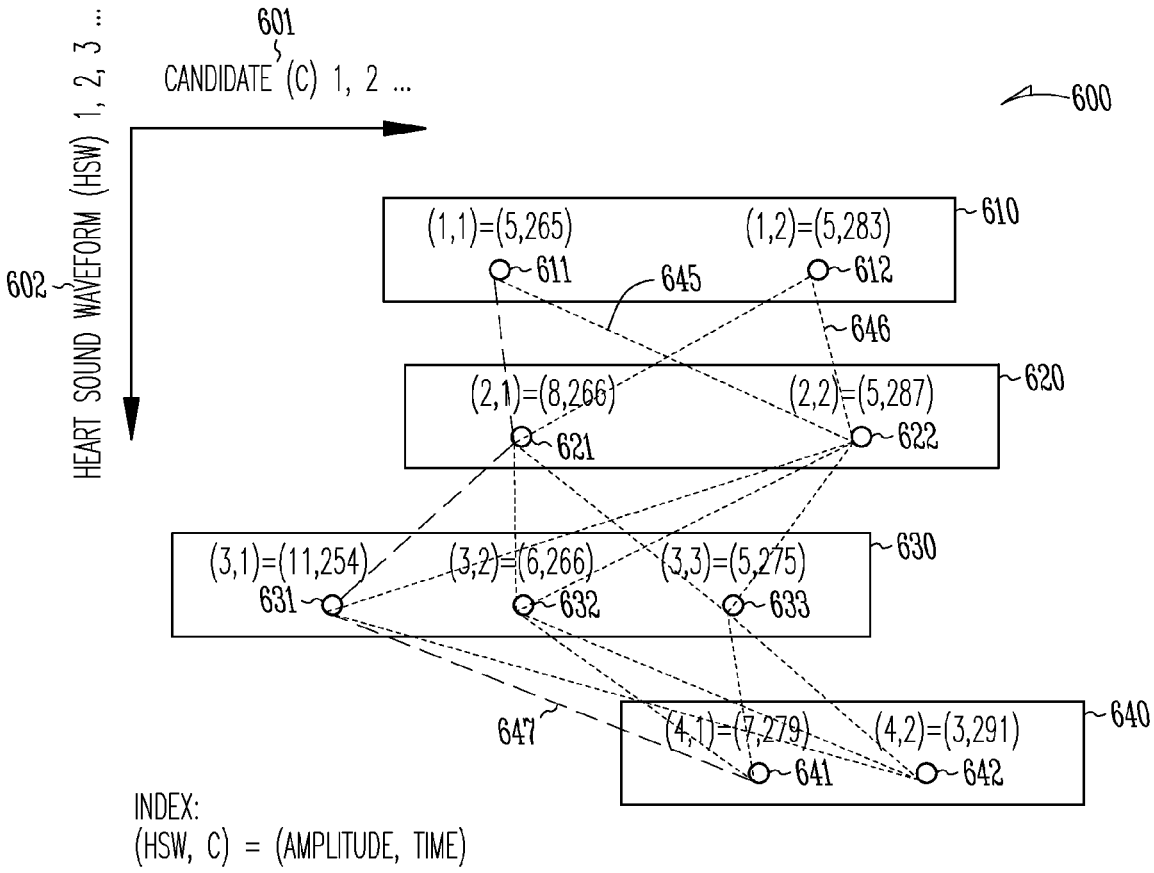
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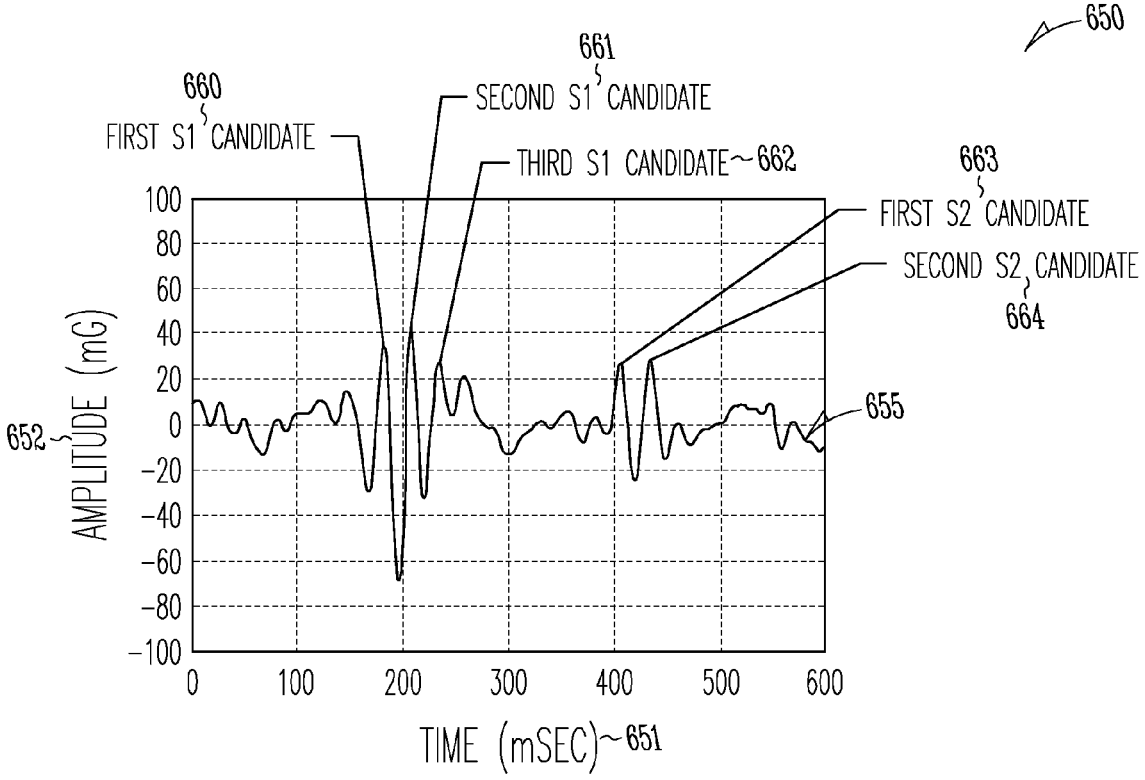
CANDIDATE (C) 1, 2 ...
600
HEART SOUND WAVEFORM (HSW) 1, 2, 3 ...
602
(1,1)=(5,265)
611
(1,2)=(5,283)
612
610
645
646
(2,1)=(8,266)
621
(2,2)=(5,287)
622
620
(3,1)=(11,254)
631
(3,2)=(6,266)
632
(3,3)=(5,275)
633
630
647
(4,1)=(7,279)
641
(4,2)=(3,291)
642
640
INDEX:
(HSW, C) = (AMPLITUDE, TIME)

Fig. 6A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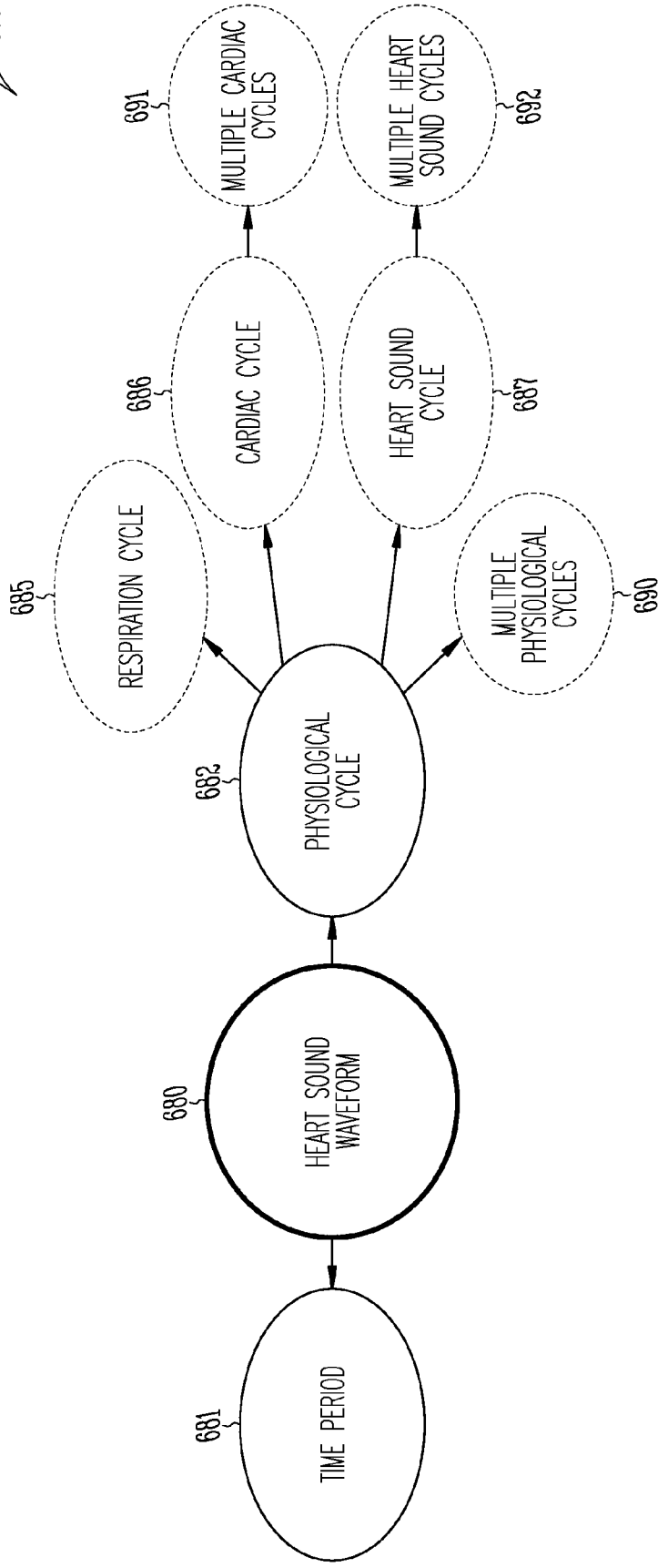
661
660
FIRST S1 CANDIDATE
SECOND S1 CANDIDATE
THIRD S1 CANDIDATE~662
663
FIRST S2 CANDIDATE
SECOND S2 CANDIDATE
664
655
652
AMPLITUDE (mG)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
100
200
300
400
500
600
TIME (mSEC)~651

Fig. 6B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691
MULTIPLE CARDIAC CYCLES
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MULTIPLE HEART SOUND CYCLES
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CARDIAC CYCLE
687
HEART SOUND CYCLE
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RESPIRATION CYCLE
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PHYSIOLOGICAL CYCLE
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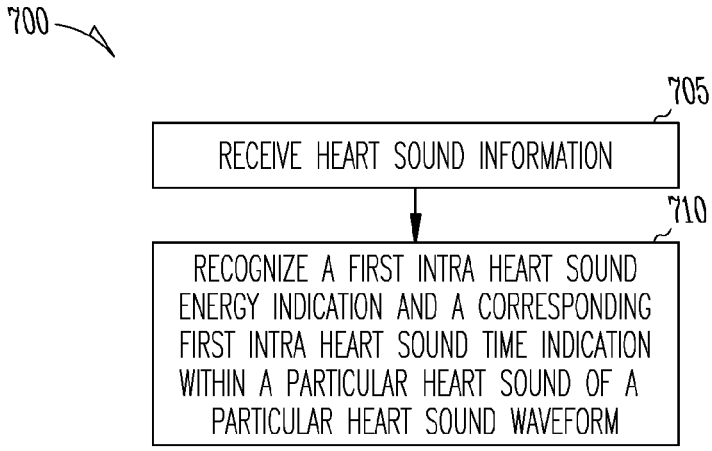
HEART SOUND WAVEFORM
681
TIME PERIOD

Fig. 6C



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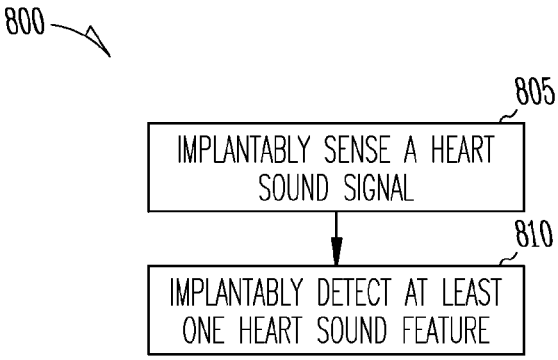

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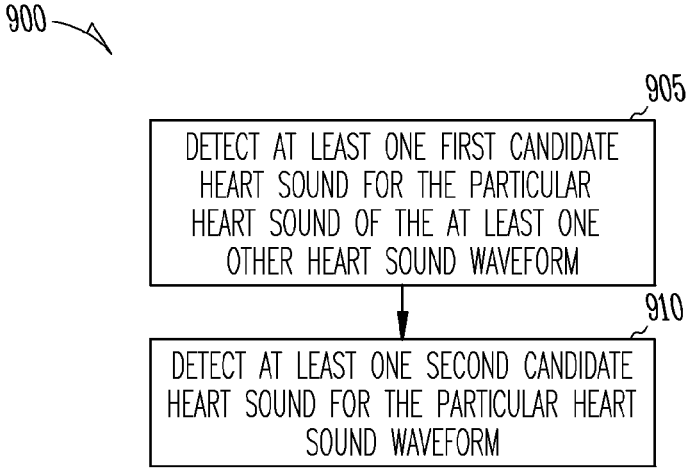

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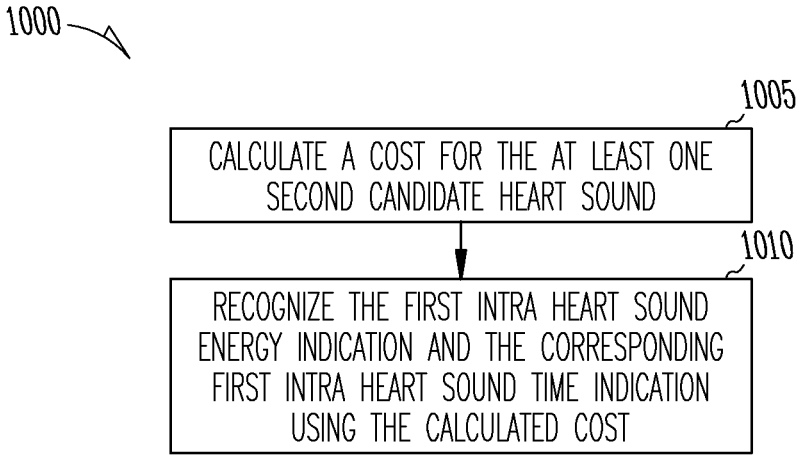

Fig. 10

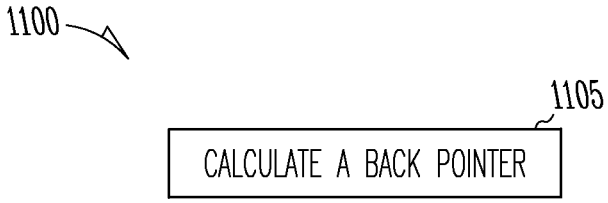

Fig. 11

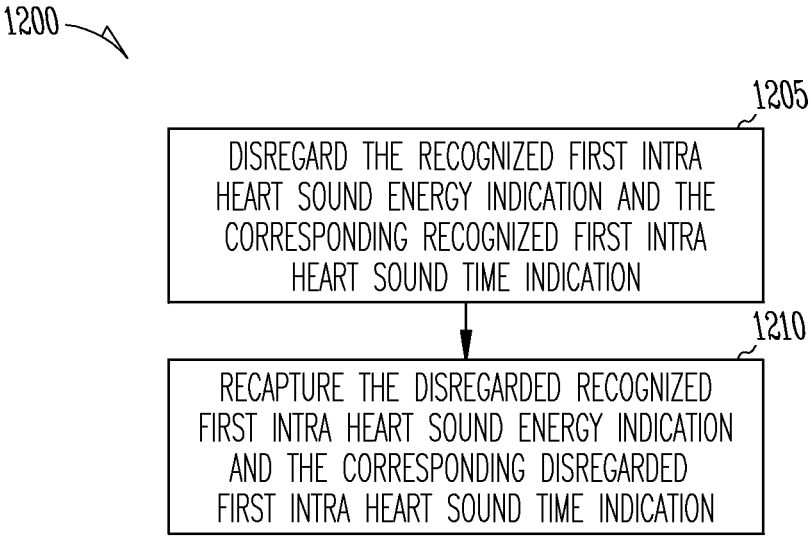

Fig. 12

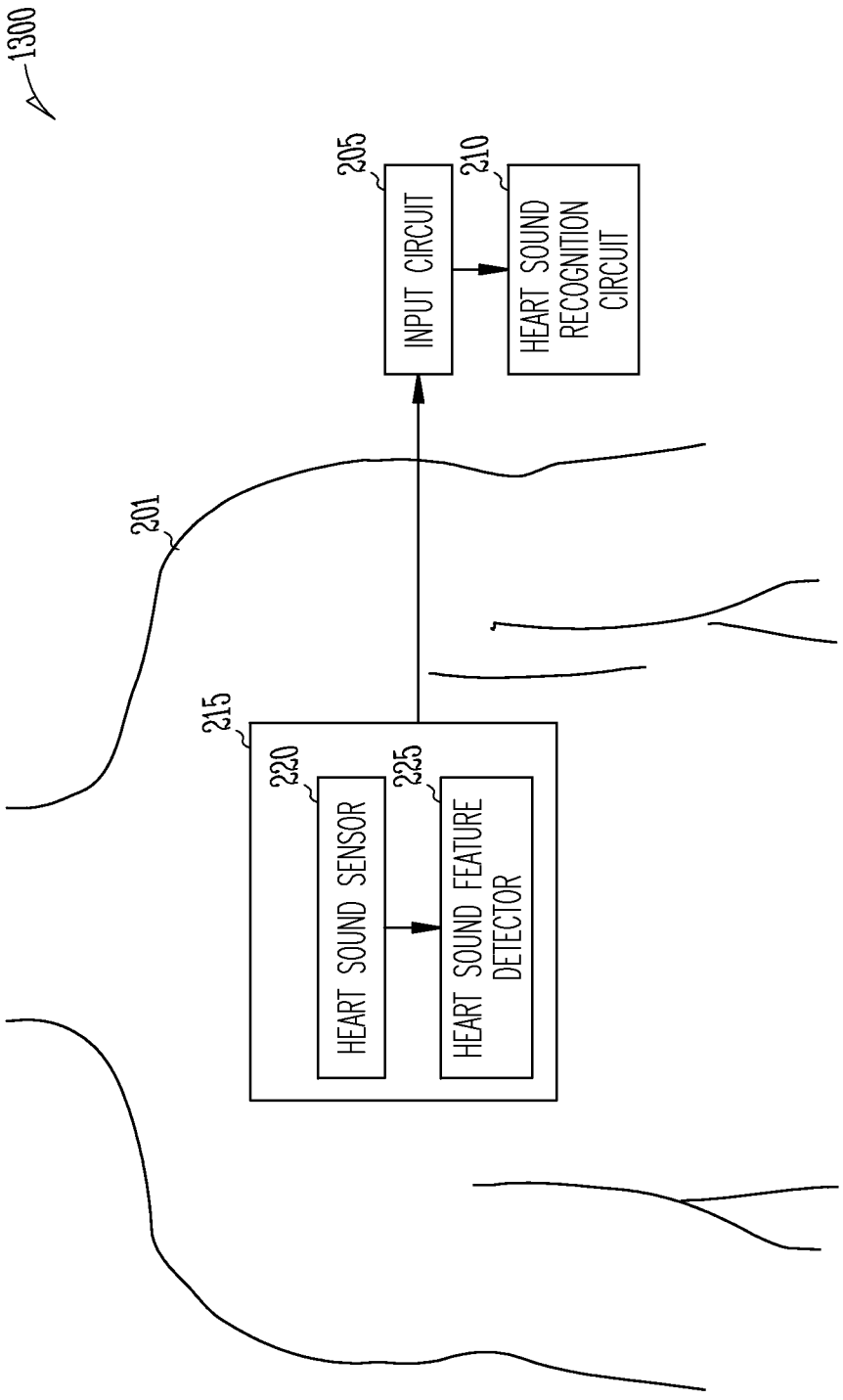
1300
205
INPUT CIRCUIT
210
HEART SOUND RECOGNITION CIRCUIT
201
215
220
HEART SOUND SENSOR
225
HEART SOUND FEATURE DETECTOR

Fig. 13

HEART SOUND TRACKING SYSTEM AND METHOD

CLAIM OF PRIORITY

This application is a continuation of and claims the benefit of priority under 35 U.S.C. §120 to Patangay et al., U.S. patent application Ser. No. 12/964,902, entitled "HEART SOUND TRACKING SYSTEM AND METHOD," filed on Dec. 10, 2010, now issued as U.S. Pat. No. 8,332,034, which is a continuation of and claims the benefit of priority under 35 U.S.C. §120 to Patangay et al., U.S. patent application Ser. No. 11/736,055, entitled "HEART SOUND TRACKING SYSTEM AND METHOD," filed on Apr. 17, 2007, now issued as U.S. Pat. No. 7,853,327, which is hereby incorporated by reference herein in its entirety.

TECHNICAL FIELD

This patent document pertains generally to cardiac health, and more particularly, but not by way of limitation, to heart sounds tracking.

BACKGROUND

Heart sounds are generally associated with the mechanical vibrations from the activity of a subject's heart and the flow of blood through the heart. Because of this association, heart sounds typically recur with each cardiac cycle of a heart, and are typically separated and classified into one of four types according to the activity associated with the vibration: S1, S2, S3, and S4. S1 (commonly referred to in the art as "the first heart sound") is typically associated with the vibrational sound made by the heart during tensing of the mitral valve. S2 (commonly referred to in the art as "the second heart sound") is typically associated with the beginning of diastole. S3 (commonly referred to in the art as "the third heart sound") and S4 (commonly referred to in the art as "the fourth heart sound") are typically associated with the filling pressures of the left ventricle during diastole. Generally, heart sounds can be used as indications of proper or improper functioning of a subject's heart.

OVERVIEW

A heart sound is typically identified according to its amplitude and corresponding timing. In one example, a heart sound can be detected using a heart sound window established according to certain triggering events, such as certain components of an electrocardiogram ("ECG") signal. One method of identifying the heart sound includes detecting the maximum heart sound amplitude within the heart sound window. The heart sound, for that heart sound window, is then identified according to the value of the maximum heart sound amplitude and corresponding timing of the maximum amplitude. However, multiple peaks can be present within the heart sound signal of an individual heart sound. The present inventors have recognized, among other things, that the peak in the heart sound signal having the maximum amplitude may not be a desirable identifier of the heart sound.

This document discusses, among other things, a system and method for heart sound tracking, including an input circuit, configured to receive heart sound information, and a heart sound recognition circuit. The heart sound recognition circuit can be coupled to the input circuit and can be configured to recognize, within a particular heart sound of a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform. The particular heart sound can include at least a portion of one of S1, S2, S3, and S4. Further, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can correspond to the at least a portion of one of S1, S2, S3, and S4, respectively.

In Example 1, a system includes an input circuit, configured to receive heart sound information. The system also includes a heart sound recognition circuit, coupled to the input circuit, configured to recognize, within a particular heart sound of a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform. In this example, the particular heart sound includes at least a portion of one of S1, S2, S3, and S4, and the first intra heart sound energy indication and the corresponding first intra heart sound time indication corresponds to the at least a portion of one of S1, S2, S3, and S4, respectively.

In Example 2, the input circuit of Example 1 is optionally configured to receive S2 information, and the heart sound recognition circuit is optionally configured to recognize, within the S2 of the particular heart sound waveform, an intra S2 energy indication and a corresponding intra S2 time indication using the S2 information from the particular heart sound waveform and the S2 information from at least one other heart sound waveform.

In Example 3, the heart sound waveform of Examples 1-2 optionally includes at least a portion of at least one physiological cycle.

In Example 4, the physiological cycle of Examples 1-3 optionally includes a cardiac cycle.

In Example 5, the particular heart sound of a particular heart sound waveform of Examples 1-4 optionally includes an ensemble averaged heart sound over multiple physiological cycles.

In Example 6, the at least one other heart sound waveform of Examples 1-5 optionally includes an immediately preceding heart sound waveform to the particular heart sound waveform.

In Example 7, the heart sound recognition circuit of Examples 1-6 is optionally configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using a heart sound template.

In Example 8, the heart sound template of Examples 1-7 optionally includes at least a portion of the heart sound information from the at least one other heart sound waveform.

In Example 9, the heart sound recognition circuit of Examples 1-8 is optionally configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using a cross correlation between at least a portion of the heart sound information from the particular heart sound waveform and at least a portion of the heart sound template.

In Example 10, the system of Examples 1-9 optionally includes an implantable medical device, including a heart sound sensor configured to sense a heart sound signal, and a heart sound feature detector, coupled to the heart sound sensor, the heart sound feature detector configured to detect at least one heart sound feature using the heart sound signal. In this example, the heart sound information of Examples 1-9 optionally includes the at least one heart sound feature.

In Example 11, the heart sound recognition circuit of Examples 1-10 optionally includes a detection circuit configured to: detect at least one first candidate heart sound for the particular heart sound of the at least one other heart sound waveform using the heart sound information, wherein the at least one first candidate heart sound includes an intra heart sound energy indication and a corresponding intra heart sound time indication; and detect at least one second candidate heart sound for the particular heart sound of the particular heart sound waveform using the heart sound information, wherein the at least one second candidate heart sound includes an intra heart sound energy indication and a corresponding intra heart sound time indication. In this example, the heart sound recognition circuit of Examples 1-10 is optionally configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using: the at least one detected first candidate heart sound; and the at least one detected second candidate heart sound.

In Example 12, the at least one other heart sound waveform of Examples 1-11 optionally includes an immediately preceding heart sound waveform to the particular heart sound waveform.

In Example 13, the heart sound recognition circuit of Examples 1-12 optionally includes a cost analysis circuit, coupled to the detection circuit, the cost analysis circuit configured to calculate a cost for the at least one second candidate heart sound, the calculated cost including: a jump penalty indicative of a temporal cost associated with the at least one second candidate heart sound; and a local score indicative of a local benefit associated with the at least one second candidate heart sound. In this example, the heart sound recognition circuit of Examples 1-12 is optionally configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the calculated cost.

In Example 14, the heart sound recognition circuit of Examples 1-13 is optionally configured to calculate a back pointer that indicates a pointer from the at least one second candidate heart sound to an optimal at least one first candidate heart sound using the cost analysis.

In Example 15, the heart sound recognition circuit of Examples 1-14 optionally includes a coasting circuit, coupled to the heart sound recognition circuit, configured to disregard the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication using a comparison of: the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication; and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

In Example 16, the heart sound recognition circuit of Examples 1-15 optionally includes a recapture circuit, coupled to the coasting circuit, configured recapture the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication using a comparison of: the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication; and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

In Example 17, a system includes means for receiving heart sound information, such as by using an input circuit to receive heart sound information. The system also includes means for recognizing a first intra heart sound energy indication and a corresponding first intra heart sound time indication within a particular heart sound of a particular heart sound waveform using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform, such as by using a heart sound recognition circuit configured to recognize, within a particular heart sound of a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform.

In Example 18, the system of Example 17 optionally includes means for disregarding the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication, such as by using a coasting circuit configured to disregard the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication using a comparison of: the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication; and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

In Example 19, the system of examples 17-18 optionally includes means for recapturing the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication, such as by using a recapture circuit configured recapture the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication using a comparison of: the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication; and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

In Example 20, a method includes receiving heart sound information. The method also includes recognizing a first intra heart sound energy indication and a corresponding first intra heart sound time indication within a particular heart sound of a particular heart sound waveform using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform. In this example, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication within the particular heart sound includes recognizing within at least a portion of one of S1, S2, S3, and S4, and the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication corresponds to the at least a portion of one of S1, S2, S3, and S4, respectively.

In Example 21, the receiving the heart sound information of Example 20 optionally includes receiving S2 information, and the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication within the particular heart sound of the particular heart sound waveform of Example 20 optionally includes recognizing an intra S2 energy indication and a corresponding intra

S2 time indication within an S2 of the particular heart sound waveform. In this example, the using the heart sound information from the particular heart sound waveform and the heart sound information from the at least one other heart sound waveform of Example 20 optionally includes using the S2 information from the particular heart sound waveform and the S2 information from at least one other heart sound waveform.

In Example 22, the heart sound waveform of Examples 20-21 optionally includes at least a portion of at least one physiological cycle.

In Example 23, the physiological cycle of Examples 20-22 optionally includes a cardiac cycle.

In Example 24, the particular heart sound of the particular heart sound waveform of Examples 20-23 optionally includes an ensemble averaged heart sound over multiple physiological cycles.

In Example 25, the using the heart sound information from the at least one other heart sound waveform of Examples 20-24 optionally includes using the heart sound information from an immediately preceding heart sound waveform to the particular heart sound waveform.

In Example 26, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication of Examples 20-25 optionally includes using a heart sound template and comparing the heart sound information from the particular heart sound waveform to the heart sound template.

In Example 27, the using the heart sound template of Examples 20-26 optionally includes updating the heart sound template using at least a portion of the heart sound information from the at least one other heart sound waveform.

In Example 28, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication of Examples 20-27 optionally includes cross correlating between at least a portion of the heart sound information from the particular heart sound waveform and at least a portion of the heart sound template.

In Example 29, the method of Examples 20-28 optionally includes implantably sensing a heart sound signal and implantably detecting at least one heart sound feature using the heart sound signal. In this example, the using the heart sound information of Examples 20-28 optionally includes using the at least one heart sound feature.

In Example 30, the method of Examples 20-29 optionally includes detecting at least one first candidate heart sound for the particular heart sound of the at least one other heart sound waveform using the heart sound information, wherein detecting the at least one first candidate heart sound includes detecting an intra heart sound energy indication and a corresponding intra heart sound time indication, and detecting at least one second candidate heart sound for the particular heart sound of the particular heart sound waveform using the heart sound information, wherein detecting the at least one second candidate heart sound includes detecting an intra heart sound energy indication and a corresponding intra heart sound time indication. In this example, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication of Examples 20-29 optionally includes using: the at least one detected first candidate heart sound; and the at least one detected second candidate heart sound.

In Example 31, the recognizing the at least one first candidate heart sound for the particular heart sound of the at least one other heart sound waveform of Examples 20-30 optionally includes recognizing the at least one first candidate heart sound for the particular heart sound of an immediately preceding heart sound waveform to the particular heart sound waveform.

In Example 32, the method of Examples 20-31 optionally includes calculating a cost for the at least one second candidate heart sound, including: calculating a jump penalty indicative of a temporal cost associated with the at least one second candidate heart sound; and calculating a local score indicative of a local benefit associated with the at least one second candidate heart sound. In this example, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication of Examples 20-31 optionally includes using the calculated cost.

In Example 33, the method of Examples 20-32 optionally includes calculating a back pointer that indicates a pointer from the at least one second candidate heart sound to an optimal at least one first candidate heart sound using the cost analysis.

In Example 34, the method of Examples 20-33 optionally includes disregarding the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication using a comparison of: the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication; and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

In Example 35, the method of Examples 20-34 optionally includes recapturing the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication using a comparison of: the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication; and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

This overview is intended to provide an overview of the subject matter of the present patent application. It is not intended to provide an exclusive or exhaustive explanation of the invention. The detailed description is included to provide further information about the subject matter of the present patent application.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, which are not necessarily drawn to scale, like numerals describe substantially similar components throughout the several views. Like numerals having different letter suffixes represent different instances of substantially similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

FIG. **1** illustrates generally an example of an illustration of portions of a heart sound signal including S1 and S2.

FIG. **2** illustrates generally an example of a system including an input circuit and a heart sound recognition circuit.

FIG. **3** illustrates generally an example of portions of a system including an implantable medical device, the implantable medical device including a heart sound sensor and a heart sound feature detector.

FIG. **4** illustrates generally an example of portions of a system including a heart sound recognition circuit, the heart sound recognition circuit including a detection circuit and a cost analysis circuit.

FIG. **5** illustrates generally an example of portions of a system including a heart sound recognition circuit, the heart sound recognition circuit including a coasting circuit and a recapture circuit.

FIG. **6**A illustrates generally an example of a relationship between multiple candidate heart sounds from multiple heart sound waveforms.

FIG. **6**B illustrates generally an example of an illustration including a heart sound signal and multiple heart sound candidates.

FIG. **6**C illustrates generally a diagram including a heart sound waveform and exemplary heart sound waveforms.

FIG. **7** illustrates generally an example of a method including receiving heart sound information and recognizing a first intra heart sound energy indication and a corresponding first intra hear sound time indication within a particular heart sound of a particular heart sound waveform.

FIG. **8** illustrates generally an example of portions of a method including implantably sensing a heart sound signal and implantably detecting at least one heart sound feature.

FIG. **9** illustrates generally an example of portions of a method including detecting at least one candidate heart sound for the particular heart sound of the particular heart sound waveform and the at least one other heart sound waveform.

FIG. **10** illustrates generally an example of portions of a method including calculating a cost for at least one candidate heart sound and recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the calculated cost.

FIG. **11** illustrates generally an example of portions of a method including calculating a back pointer.

FIG. **12** illustrates generally an example of portions of a method including disregarding the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication and recapturing the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication.

FIG. **13** illustrates generally an example of a system including an implantable medical device, an input circuit, and a heart sound recognition circuit. The implantable medical device includes a heart sound sensor and a heart sound feature detector.

DETAILED DESCRIPTION

The following detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention may be practiced. These embodiments, which are also referred to herein as "examples," are described in enough detail to enable those skilled in the art to practice the invention. The embodiments may be combined, other embodiments may be utilized, or structural, logical and electrical changes may be made without departing from the scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims and their equivalents.

In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one. In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. Furthermore, all publications, patents, and patent documents referred to in this document are incorporated by reference herein in their entirety, as though individually incorporated by reference. In the event of inconsistent usages between this document and those documents so incorporated by reference, the usage in the incorporated reference(s) should be considered supplementary to that of this document; for irreconcilable inconsistencies, the usage in this document controls.

Heart sounds include S1 (or the "first heart sound"), S2 (or "the second heart sound"), S3 (or "the third heart sound"), S4 (or "the fourth heart sound"), and their various sub-components. S1 is believed to be indicative of, among other things, mitral valve closure, tricuspid valve closure, and aortic valve opening. S2 is believed to be indicative of, among other things, aortic valve closure and pulmonary valve closure. S3 is believed to be a ventricular diastolic filling sound often indicative of certain pathological conditions, including heart failure. S4 is believed to be a ventricular diastolic filling sound resulted from atrial contraction and is believed usually indicative of pathological conditions. The term "heart sound" hereinafter refers to any indication of a heart sound (e.g., S1, S2, etc.) or any component thereof (e.g., M1 component of S1 (indicative of mitral valve closure), A2 component of S2 (indicative of aortic valve closure), P2 component of S2 (indicative of pulmonic valve closure), etc.).

A heart sound can include audible or inaudible mechanical vibrations caused by cardiac activity. In certain examples, heart sounds can be sensed with an accelerometer. Such mechanical vibrations can be conceptualized as providing acoustic energy.

The present inventors have recognized, among other things, that the maximum amplitude of a heart sound signal may not be the most desirable identifier of the heart sound. For example, a first intra heart sound energy indication and a corresponding first intra heart sound time indication for a particular heart sound of a particular heart sound waveform can be recognized, such as by using heart sound information from multiple heart sound waveforms. In an example, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can be recognized using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform. The recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication can be indicative or characteristic of a desirable heart sound amplitude and timing within the particular heart sound waveform.

FIG. **1** illustrates generally an example of an illustration **100** including portions of a heart sound signal **115**, including S1 **120** and S2 **125**, shown with respect to Amplitude (mG) **110** and Time (msec) **105**, where mG are units of acceleration that are produced when an accelerometer is used to measure the vibrations produced by the heart sounds.

A heart sound signal can include multiple peaks. In this example, the S1 **120** portion of the heart sound signal **115** has multiple peaks, such as peak **121**, peak **122**, and peak **123**, and the S2 **125** portion of the heart sound signal **115** has multiple peaks, such as peak **126** and peak **127**. In an example, the timing and amplitude of S1 can be determined using the information from the current S1, such as by selecting the largest amplitude in the S1 **120** portion of the heart sound signal **115** and its corresponding timing. However, the present inventors have recognized, among other things, that the peak having the largest amplitude may not be the best identifier of the heart sound. In certain examples, a more desirable heart sound identifier can be attained using the information from the current S1, as well as information from an S1 of another heart sound cycle. In certain examples, the largest amplitude in a heart sound signal can include noise or other undesirable artifacts, or the largest amplitude may be an anomaly. In

certain instances, the anomaly may contain valuable information. However, in other instances, the anomaly can undesirably influence the overall heart sound data. Thus, in certain examples, peak **121** or peak **123** and their corresponding timings could be a more desirable identifier for the S1 **120** portion of the heart sound signal **115**.

FIG. **2** illustrates generally an example of a system **200** including an input circuit **205** and a heart sound recognition circuit **210**. The input circuit **205** can be configured to receive heart sound information. The heart sound recognition circuit **210** can be configured to recognize, within a particular heart sound of a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication. In an example, the heart sound recognition circuit **210** can recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication, such as by using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform.

In certain examples, the input circuit **205** can be configured to receive heart sound information from a heart sound sensor or other sensor configured to sense, detect, or otherwise collect heart sound information. In certain examples, the input circuit **205** can be configured to receive heart sound information from another device, such as an external programmer, a memory, or other device capable of having heart sound information.

The heart sound information can include any information indicative of a heart sound (e.g., the acoustic or mechanical energy of a heart). In certain examples, the heart sound information can include at least a portion of at least one heart sound signal, such as an entire heart sound signal, features of a heart sound signal, or multiple heart sound signals. The heart sound information can include at least a portion of S1 information, S2 information, S3 information, S4 information, or other heart sound information.

In this example, the heart sound recognition circuit **210** can be coupled to the input circuit **205**. The heart sound recognition circuit **210** can be configured to receive information (e.g., heart sound information) from the input circuit **205**. In certain examples, the heart sound recognition circuit **210** can include the input circuit **205**, or the heart sound recognition circuit **210** or the input circuit **205** can be implemented using a processor, a programmer, controller, or the like.

In an example, the particular heart sound can include at least one of S1, S2, S3, S4, or other portions or components of a heart sound signal. Further, the particular heart sound can include at least a portion of one of S1, S2, S3, S4, or other portions or components of a heart sound signal, such as at least a portion of S1, the aortic valve component of S2 (commonly referred to as the A2 component of S2), the pulmonic valve component of S2 (commonly referred to as the P2 component of S2), etc.

In an example, the heart sound waveform can include at least a portion of at least one physiological cycle. Generally, the body functions in physiological cycles. In certain examples, a physiological cycle can include a cardiac cycle, a respiration cycle, or other physiological cycle of the body. The physiological cycle can be detected using an electrical signal (e.g., an electrocardiogram (ECG) or an impedance signal indicative of cardiac or respiratory activity), or the physiologic cycle can be detected using other signals, such as by using a mechanical signal (e.g., a pressure signal indicative of cardiac or respiratory activity or a heart sound signal indicative of cardiac activity). In an example, the heart sound waveform can include at least a portion of at least one physiological cycle, such as a portion of the cardiac cycle or a portion of the respiration cycle. In other examples, the heart sound waveform can include multiple physiological cycles, such as multiple cardiac cycles. In other examples, the heart sound waveform can include a specified time period, such as a 10-minute time period, or other time period.

In an example, the particular heart sound of the particular heart sound waveform can include an ensemble average of the particular heart sound over a heart sound waveform, such as that disclosed in the commonly assigned Siejko et al. U.S. Pat. No. 7,115,096 entitled "THIRD HEART SOUND ACTIVITY INDEX FOR HEART FAILURE MONITORING," which is hereby incorporated by reference in its entirety, including its disclosure of ensemble averaging an acoustic signal. In certain examples, the ensemble average of the particular heart sound over multiple heart sound waveforms can include at least a portion of the S1 (or at least a portion of another heart sound, such as S2, S3, S4, etc.) over a heart sound waveform, such as over multiple physiological cycles (e.g., multiple cardiac cycles) or over a specified time period (e.g., 1 minute, 10 minutes, 1 hour, 1 day, etc.).

In the example of FIG. **2**, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can be indicative of a desirable heart sound amplitude and timing within the particular heart sound waveform. In certain examples, the desirable heart sound amplitude and timing can include a combination of the heart sound amplitude having the largest or most consistent peak, peak-to-peak, peak-to-peak with zero-crossing, or other heart sound amplitude within the particular heart sound waveform, coupled with the heart sound timing having the most consistent timing of the heart sound amplitude events (e.g., the peak, peak-to-peak, peak-to-peak with zero-crossing, or other heart sound amplitude within the particular heart sound waveform).

In an example, the first intra heart sound energy indication can include an energy (e.g., an amplitude) within the particular heart sound waveform (e.g., within the S1, S2, etc.). Similarly, the corresponding first intra heart sound time indication can include a time within the particular heart sound waveform (e.g., within the S1, S2, etc.). In certain examples, the first intra heart sound time can include the time associated with the first intra heart sound amplitude, or the first intra heart sound time can include a time different or independent from the first intra heart sound amplitude.

In an example, the particular heart sound waveform can include a current heart sound waveform. In certain examples, the system **200** can be configured to operate in real-time, or the system **200** can be configured to operate using stored data (e.g., stored or buffered heart sound information). In certain examples, the at least one other heart sound waveform can include at least one heart sound waveform occurring previous to, occurring after, or occurring at a combination of previous to or after the particular heart sound waveform. In an example, the at least one other heart sound waveform can include the immediately preceding heart sound waveform to the particular heart sound waveform.

For example, in the example of FIG. **6**A, four heart sound waveforms are displayed: a first heart sound waveform **610**, a second heart sound waveform **620**, a third heart sound waveform **630**, and a fourth heart sound waveform **640**. In an example, the particular heart sound waveform can include the third heart sound waveform **630**. In this example, the at least one other heart sound waveform can include at least one of the first heart sound waveform **610**, the second heart sound waveform **620**, and the fourth heart sound waveform **640**.

In an example, the input circuit **205** can be configured to receive S2 information. The heart sound recognition circuit

210 can be configured to recognize an intra S2 energy indication and a corresponding intra S2 time indication within the S2 of the particular heart sound waveform. In an example, the heart sound recognition circuit **210** can be configured to recognize the intra S2 energy indication and the corresponding intra S2 time indication using the S2 information from the particular heart sound waveform and also using the S2 information from at least one other heart sound waveform.

In an example, the heart sound recognition circuit **210** can be configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using a heart sound template, such as by comparing the heart sound information from the particular heart sound waveform to the heart sound template. In an example, the heart sound information can include at least one heart sound feature, such as a morphological feature. Thus, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can be recognized by comparing at least one heart sound feature, such as a morphological feature, of the heart sound information from the particular heart sound waveform to the heart sound template.

In certain examples, a heart sound template can include previously attained heart sound information from a subject (e.g., a subject on which system **200** is configured to perform) or a population (e.g., one or more other subjects, such as subjects having normal cardiac health, subjects having a specific physiological condition, etc.). In an example, the heart sound information can include at least one heart sound feature, such as a morphological feature. In an example, the previously attained heart sound information can include at least a portion of the heart sound information from the at least one other heart sound waveform of the subject. In certain examples, the previously attained heart sound information can include heart sound information from a heart sound waveform that occurs previous to the particular heart sound. In certain examples, the previously attained heart sound information can include heart sound information from a heart sound waveform that occurs later in time than the particular heart sound waveform, such as when the heart sound recognition circuit **210** is recognizing using stored or buffered heart sound information.

In an example, the heart sound template can be updated using the heart sound information from the subject, such as the heart sound information from the particular heart sound waveform or the heart sound information from the at least one other heart sound waveform.

Further, in certain examples of FIG. **2**, the heart sound recognition circuit **210** can be configured to recognize the first intra heart sound energy indication or the corresponding first intra heart sound time indication using a cross correlation between (1) at least a portion of the heart sound information from the particular heart sound waveform, such as at least one heart sound feature (e.g., at least one morphological feature), and (2) at least a portion of the heart sound template.

In an example, the heart sound recognition circuit **210** can be configured to produce at least one table. The table can include the recognized intra heart sound energy indication and the corresponding first intra heart sound time indication. In an example, the table can be stored in memory, and can provide a compact representation of heart sound information.

FIG. **3** illustrates generally an example of portions of a system **300** including an implantable medical device **215** including a heart sound sensor **220** and a heart sound feature detector **225**.

In this example, the heart sound sensor **220** can be configured to sense a heart sound signal of a subject. The heart sound signal can include any signal that includes an indication of at least a portion of the at least one heart sound of the subject (e.g. S1, S2, S3, S4, or any components thereof, such as A2, P2, etc.). The heart sound sensor **220** can be configured to produce a heart sound signal, such as an electrical or optical representation of a heart sound signal, that includes information about the acoustic or vibrational heart sound signal of the subject. The heart sound sensor **220** can include any device configured to sense the heart sound signal of the subject. In certain examples, the heart sound sensor **220** can include an implantable sensor including at least one of an accelerometer, an acoustic sensor, a microphone, etc.

In an example, the heart sound sensor **220** can include an accelerometer configured to sense an acceleration signal indicative of the heart sound of the subject, such as that disclosed in the commonly assigned Carlson et al. U.S. Pat. No. 5,792,195 entitled "ACCELERATION SENSED SAFE UPPER RATE ENVELOPE FOR CALCULATING THE HEMODYNAMIC UPPER RATE LIMIT FOR A RATE ADAPTIVE CARDIAC RHYTHM MANAGEMENT DEVICE," which is hereby incorporated by reference in its entirety including its disclosure of accelerometer detection of heart sounds, or such as that disclosed in the commonly assigned Siejko et al. U.S. patent application Ser. No. 10/334,694, now issued as U.S. Pat. No. 7,972,275, entitled "METHOD AND APPARATUS FOR MONITORING OF DIASTOLIC HEMODYNAMICS," filed Dec. 30, 2002 (herein "Siejko et al. '694"), which is hereby incorporated by reference in its entirety including its disclosure of accelerometer detection of heart sounds. In other examples, other accelerometer or acceleration sensor configurations can be used to sense the heart sound signal.

In another example, the heart sound sensor **220** can include an acoustic sensor configured to sense an acoustic energy indicative of the heart sound of the subject, such as that disclosed in the commonly assigned Siejko et al. '694, incorporated by reference in its entirety. In other examples, other acoustic sensor or microphone configurations can be used to sense the heart sound signal.

In the example of FIG. **3**, the heart sound feature detector **225** is coupled to the heart sound sensor **220**. The heart sound feature detector **225** can be configured to receive the heart sound signal from the heart sound sensor **220**. The heart sound feature detector **225** can be configured to detect at least one feature of at least a portion of at least one heart sound. The heart sound feature can include at least one measurement, characteristic, morphology, computation, or interval of at least a portion of at least one heart sound. In certain examples, this includes at least one of an amplitude of a heart sound signal, a magnitude of a heart sound signal, a total energy of a heart sound signal, a peak of a heart sound signal, etc. (e.g., an amplitude or magnitude of at least one peak, at least one valley, or at least one other portion of an S1, an amplitude or magnitude of at least one peak, at least one valley, or at least one other portion of an S2, etc.).

In an example, the heart sound information used by the heart sound recognition circuit **210** can include the detected at least one heart sound feature. In certain examples, the heart sound sensor **220** can include the heart sound feature detector **225**, or the heart sound feature detector **225** can include the heart sound sensor **220**.

FIG. **4** illustrates generally an example of portions of a system **400** including a heart sound recognition circuit **210**, the heart sound recognition circuit **210** including a detection circuit **230** and a cost analysis circuit **235**.

In an example, the detection circuit **230** can be configured to detect at least one first candidate heart sound for the particular heart sound of the at least one other heart sound wave-

form. In an example, the detection circuit **230** can detect the at least one first candidate heart sound using the heart sound information. The at least one first candidate heart sound can include an intra heart sound energy indication and a corresponding intra heart sound time indication. In an example, the candidate heart sound can be identified or characterized, such as by using the intra heart sound energy indication and the corresponding intra heart sound time indication. A candidate heart sound can include any portion, component, or identifier of the heart sound signal, the heart sound information, or the at least one heart sound feature for a heart sound of a heart sound waveform. In an example, the first candidate heart sound can include at least one feature (e.g., a positive peak, a negative peak, etc.) of the particular heart sound of the at least one other heart sound waveform, the at least one feature having an intra heart sound energy indication associated with the at least one feature (e.g., the amplitude of the positive peak, the amplitude of the negative peak, etc.) and a corresponding intra heart sound time indication associated with the at least one feature.

In an example, the detection circuit **230** can be configured to detect at least one second candidate heart sound for the particular heart sound of the particular heart sound waveform. In an example, the detection circuit **230** can detect the at least one second candidate heart sound using the heart sound information. The at least one second candidate heart sound can include an intra heart sound energy indication and a corresponding intra heart sound time indication. In an example, the candidate heart sound can be identified or characterized using the intra heart sound energy indication and the corresponding intra heart sound time indication. In an example, the second candidate heart sound can include at least one feature (e.g., a positive peak, a negative peak, etc.) of the particular heart sound of the particular heart sound waveform, the at least one feature having an intra heart sound energy indication associated with the at least one feature (e.g., the amplitude of the positive peak, the amplitude of the negative peak, etc.) and a corresponding intra heart sound time indication associated with the at least one feature.

In the example of FIG. **4**, the heart sound recognition circuit **210** can be configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the at least one detected first candidate heart sound and the at least one detected second candidate heart sound. The first intra heart sound energy indication and the corresponding first intra heart sound time indication can be recognized using a relationship between the at least one detected first candidate heart sound and the at least one detected second candidate heart sound, such as by calculating a cost from the at least one detected first candidate heart sound to the at least one detected second candidate heart sound.

In an example, the cost analysis circuit **235** can be coupled to the detection circuit **230**. The cost analysis circuit **235** can be configured to use a dynamic programming method, such as a Viterbi method or other dynamic programming method, to determine a desirable heart sound candidate for the particular heart sound waveform. In an example, the desirable heart sound candidate can include a candidate having the least cost. For example, by selecting "desirable" heart sound indications from among multiple candidates, in a manner that tends to reduce or minimizes the cost function over many cardiac cycles, the present methods can be used to track the more desirable heart sound indications.

In an example, the cost analysis circuit **235** can be configured to calculate a cost for each second candidate heart sound. In an example, the cost can be calculated for the second candidate heart sound using at least one of a jump penalty and a local score. For example, the jump penalty can include a temporal cost associated with the second candidate heart sound. In an example, the temporal cost can include a time difference between the second candidate heart sound and a first candidate heart sound (see, e.g., FIG. **6**). The local score can include a local benefit associated with the at least one second candidate heart sound. In an example, the local score includes the amplitude of the second heart sound candidate. In an example, the local score or the jump penalty can be weighted (e.g., by multiplying the local score or the jump penalty by a scaling factor) to further tailor the cost analysis.

In an example, the heart sound recognition circuit **210** can be configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the calculated cost, such as by selecting the heart sound candidate for the particular heart sound waveform having a lowest cost or a highest benefit.

In an example, the cost analysis can include a total score. The total score can factor in at least one of the jump penalty for a candidate heart sound having a temporal cost and the local score for the candidate heart sound having a local benefit. In an example, the total score ("D(t,x)") can be calculated by taking the difference of the jump penalty ("J(x',x)") from a previous total score ("D(t−1,x')"), and by adding the local score ("$d(X_t,x)$") to the maximum result of the difference:

$$D(t, x) = \max_{x' \in M(x)} \{D(t-1, x') - J(x', x)\} + d(X_t, x), \quad \text{(Eq. 1)}$$

wherein t denotes a heart sound waveform, x denotes a candidate heart sound, and M(x) includes a set of possible predecessors of x.

In an example, the heart sound recognition circuit **210** can be configured to calculate a back pointer. In an example, the back pointer can indicate a pointer from the at least one second candidate heart sound to a desirable at least one first candidate heart sound. The desirable at least one first candidate heart sound typically includes the first candidate heart sound having a maximum result of the difference between the previous total score and the current jump penalty. Thus, in an example, the back pointer ("B(t,x)") can be calculated using:

$$B(t, x) = \operatorname{argmax}_{x' \in M(x)} \{D(t-1, x') - J(x', x)\}. \quad \text{(Eq. 2)}$$

FIG. **5** illustrates generally an example of portions of a system **500** including a heart sound recognition circuit **210** including a coasting circuit **240** and, if desired, also including a recapture circuit **245**.

In an example, the coasting circuit **240** can be coupled to the heart sound recognition circuit **210**. The coasting circuit **240** can be configured to disregard the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication. In an example, if the calculated cost of a recognized first intra heart sound energy indication and corresponding first intra heart sound time indication is too high (e.g., above a threshold, or above previous results), or if the total score of the recognized first intra heart sound energy indication and corresponding first intra heart sound time indication is too low (e.g., below a threshold, or below previous results), then the coasting circuit

240 can be configured to disregard the recognized first intra heart sound energy indication and corresponding first intra heart sound time indication.

The coasting circuit **240** can be configured to coast (e.g., disregard heart sound indications that would otherwise be recognized) for a certain period (e.g., a certain number of heart sound waveforms, a certain period of time, etc.). In an example, if, at the end of the certain period, the calculated cost remains too high, or if the total score remains too low, the coasting circuit **240** will stop coasting, if so configured. Generally, if the end of the certain period is reached with the calculated cost still too high, or the total score still too low, this can be an indication that the heart sound information has changed or a problem has arisen (e.g., noise, physical condition change, system failure, etc.). In an example, if the calculated cost remains too high, or if the total score remains too low, at the end of the certain period the coasting circuit **240** can provide a notification to a user, if so configured, such as by using a notification circuit.

In an example, the coasting circuit **240** can be configured to disregard the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication based upon a result of a comparison. In an example, the comparison can include a comparison of the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

In an example, the recapture circuit **245** can be coupled to the coasting circuit **240** to provide a storage buffer for the disregarded information before discarding, so that it can be recaptured, if desired. Generally, the recapture circuit **245** can be configured to recapture the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication. In an example, if a recognized first intra heart sound energy indication and a corresponding recognized first intra heart sound time indication have been disregarded, such as by using the coasting circuit **240**, and the coasting circuit **240** recurrently reaches the end of the certain period, then it may be beneficial to recapture the disregarded recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication (e.g., it may be beneficial if the heart sound information has changed, if the subject's status has changed, etc.).

In an example, the recapture circuit **245** can be configured to recapture the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication, with the recapture triggered using a comparison. In an example, the comparison can include a comparison of the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

FIG. **6**A illustrates generally an example, using exemplary data, of a relationship **600** between multiple candidate heart sounds **611**, **612**, **621**, **622**, **631**, **632**, **633**, **641**, **642** from multiple heart sound waveforms (the first heart sound waveform **610**, the second heart sound waveform **620**, the third heart sound waveform **630**, and the fourth heart sound waveform **640**), shown with respect to candidates **601** and heart sound waveform **602**. In this example, the candidate heart sound **611** can be identified as candidate heart sound (1,1) **611**, where (1,1) refers to (heart sound waveform, candidate number of the heart sound waveform). Each candidate heart sound (e.g., candidate heart sound (1,1) **611**) is shown with its amplitude (rounded up to the nearest whole number) and corresponding time (e.g., candidate heart sound (1,1) **611** has a rounded amplitude of 5 and a corresponding time index of 265, (5,265)).

The relationship **600** illustrates an example of four heart sound waveforms, each having at least two candidate heart sounds. In an example, Table 1 (below) generally illustrates examples of calculated jump penalties associated with each candidate. In this example, the jump penalty is indicative of the temporal distance between a heart sound candidate of a particular heart sound waveform (e.g., the second heart sound waveform **620**) and a heart sound candidate of the immediately preceding heart sound waveform to the particular heart sound waveform (e.g., the first heart sound waveform **610**).

TABLE 1

J = jump penalty

(HSW, Candidate)	1	2	3
1	0	0	
2	1, 17	22, 4	
3	12, 33	0, 21	9, 12
4	25, 13, 4	37, 25, 16	

In Table 1, the candidate heart sound (1,1) **611** and the candidate heart sound (1,2) **612** are initially given jump penalties of zero, because there is no data preceding them. Further, relationship **600** shows jump paths **645**, **646**. The jump path **645** is a jump path from the candidate heart sound (1,1) **611** to the candidate heart sound (2,2) **622**. In Table 1, the jump path **645** is displayed in row 2, column 2, having a value of 22, which is representative of a shift in the time index from 265 to 287. The jump path **646** is a jump path from the candidate heart sound (1,2) **612** to the candidate heart sound (2,2) **622**.

In an example, Table 2 (below) generally illustrates the calculated total scores associated with each candidate of relationship **600** in accordance with Eq. 1, where the local score ("$d(X_t,x)$") includes the amplitude of the candidate and a gain. In this example, the gain of the local score is 5.

TABLE 2

$$D(t, x) = \max_{x' \in M(x)} \{D(t-1, x') - J(x', x)\} + d(X_t, x)$$

(HSW, Candidate)	1	2	3
1	0	0	
2	39	21	
3	82	69	55
4	92	60	

In an example, Table 3 (below) generally illustrates the calculated back pointer for each candidate of relationship **600** in accordance with Eq. 2.

TABLE 3

$$B(t, x) = \arg\max_{x' \in M(x)} \{D(t-1, x') - J(x', x)\}$$

(HSW, Candidate)	1	2	3
1	0	0	
2	1	2	
3	1	1	1
4	1	1	

FIG. **6**A also includes a traceback path **647**. In an example, the traceback path **647** can be determined using the calculated back pack pointers. In an example, a candidate was chosen at the fourth heart sound waveform **640**, such as by choosing the candidate having the highest total score. In this example, the candidate heart sound (4,1) **641** was chosen to start the traceback path. The traceback path goes to the first candidate of the previous heart sound waveform, the candidate heart sound (3,1) **631**, using the back pointer calculated for the candidate heart sound (4,1) **641**, **1**. Similarly, the traceback path continues to the first candidate of the second heart sound waveform, the candidate heart sound (2,1) **621**, using the back pointer calculated for the candidate heart sound (3,1) **631**, **1**, and so on.

FIG. **6**B illustrates generally an example of an illustration **650** including a heart sound signal **655**, shown with respect to Amplitude (mG) **652** and Time (msec) **651**, and including multiple heart sound candidates. In this example, the multiple heart sound candidates include a first S1 candidate **660**, a second S1 candidate **661**, a third S1 candidate **662**, a first S2 candidate **663**, and a second S2 candidate **664**.

In an example, the at least one first candidate heart sound for the particular heart sound of the at least one particular heart sound waveform can include (1) (for the S1 of the current heart sound cycle shown in the illustration **650**) the first S1 candidate **660**, the second S1 candidate **661**, and the third S1 candidate **662**, or (2) (for the S2 of the current heart sound cycle shown in the illustration **650**) the first S2 candidate **663** and the second S2 candidate **664**.

For example, in a relationship similar to the relationship **600** of FIG. **6**A showing S1 candidates with respect to heart sound waveforms, where the heart sound cycle of the illustration **650** is a heart sound waveform (e.g., a first heart sound waveform), the first S1 candidate **660** would be the first candidate of the heart sound waveform (e.g., candidate heart sound (1,1)), the second S1 candidate **661** would be the second candidate of the heart sound waveform (e.g., candidate heart sound (1,2)), and the third S1 candidate **662** would be the third candidate of the heart sound waveform (e.g., candidate heart sound (1,3)).

FIG. **6**C illustrates generally a diagram **670** including a heart sound waveform **680** and exemplary heart sound waveforms. The exemplary heart sound waveforms include a time period **681** and a physiological cycle **682**. The physiological cycle **682** includes multiple physiological cycles **690**, a respiration cycle **685**, a cardiac cycle **686**, multiple cardiac cycles **691**, a heart sound cycle **687**, and multiple heart sound cycles **692**. In other examples, the heart sound waveform can include at least a portion of one physiological cycle, including at least a portion of one cardiac cycle, etc. The heart sound waveform can also include multiple respiration cycles.

FIG. **7** illustrates generally an example of a method **700** including receiving heart sound information and recognizing a first intra heart sound energy indication and a corresponding first intra heart sound time indication within a particular heart sound of a particular heart sound waveform. In an example, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can be recognized using the heart sound recognition circuit **210**.

At **705**, heart sound information can be received, such as by using the input circuit **205**.

At **710**, a first intra heart sound energy indication and a corresponding first intra heart sound time indication can be recognized within a particular heart sound of a particular heart sound waveform. In an example, at **710**, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can be recognized using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform.

In an example, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication within the particular heart sound includes recognizing within at least a portion of one of S1, S2, S3, S4, or other portions or components of a heart sound signal. In an example, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication can correspond to the at least a portion of one of S1, S2, S3, S4, or other portions or components of the heart sound signal.

In the example of method **700**, receiving the heart sound information can include receiving S2 information. The recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication within the particular heart sound of the particular heart sound waveform can include recognizing an intra S2 energy indication and a corresponding intra S2 time indication within an S2 of the particular waveform. Further, the using the heart sound information from the particular heart sound waveform and the heart sound information from the at least one other heart sound waveform can include using the S2 information from the particular heart sound waveform and the S2 information from at least on other heart sound waveform.

In an example, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication can include using a heart sound template. In an example, the using the heart sound template can include comparing the heart sound information from the particular heart sound waveform to the heart sound template. In certain examples, the heart sound information from the particular heart sound waveform can include at least one heart sound feature, such as a morphological feature. In an example, the using the heart sound template can include using a cross correlation between at least a portion of the heart sound information from the particular heart sound waveform and at least a portion of the heart sound template. In an example, the using the cross correlation can include using a cross correlation between a morphology of the heart sound signal from the particular heart sound waveform and at least a portion of the heart sound template, where the morphology includes multiple heart sound features, measurements, characteristics, etc., of the heart sound signal from the particular heart sound waveform.

In an example, the heart sound template can be updated using at least a portion of the heart sound information. In certain examples, the using the at least a portion of the heart sound information can include using at least a portion of the heart sound information from the at least one other heart sound waveform.

FIG. **8** illustrates generally an example of portions of a method **800** including implantably sensing a heart sound signal and implantably detecting at least one heart sound feature. In an example, the heart sound signal can be implant-

ably sensed using the heart sound sensor **220**. In an example the at least one heart sound feature can be detected using the heart sound feature detector **225**.

At **805**, a heart sound signal can be implantably sensed. The heart sound signal can include any signal indicative of at least a portion of the at least one heart sound of the subject (e.g. S1, S2, S3, S4, or any components thereof, such as A2, P2, etc.). In an example, the heart sound signal can be sensed using the heart sound sensor **220**.

At **810**, at least one heart sound feature can be implantably detected. The at least one heart sound feature can be detected using the heart sound signal. Generally, the at least one heart sound feature can include at least one measurement, characteristic, morphology, computation, or interval of at least a portion of at least one heart sound.

FIG. **9** illustrates generally an example of portions of a method **900** including detecting at least one candidate heart sound for the particular heart sound of the particular heart sound waveform and the at least one other heart sound waveform. In an example, the at least one candidate heart sound can be detected using the detection circuit **230**.

At **905**, at least one first candidate heart sound for the particular heart sound of the at least one other heart sound waveform can be detected. In an example, the at least one first candidate heart sound can be detected using the heart sound information. The detecting the at least one first candidate heart sound can include detecting an intra heart sound energy indication and a corresponding intra heart sound time indication. Generally, the at least one other heart sound waveform excludes the particular heart sound waveform. In an example, the at least one other heart sound waveform can include the immediately preceding heart sound waveform to the particular heart sound waveform. In other examples, the at least one other heart sound waveform can include other preceding heart sound waveforms to the particular heart sound waveform, or the at least one other heart sound waveform can include heart sound waveforms occurring later in time than the particular heart sound waveform.

At **910**, at least one second candidate heart sound for the particular heart sound of the particular heart sound waveform can be detected. In an example, the at least one second candidate heart sound can be detected using the heart sound information. The detecting the at least one second candidate heart sound can include detecting an intra heart sound energy indication and a corresponding intra heart sound time indication.

In an example, the method **900** can further include recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the at least one detected first candidate heart sound and the at least one detected second candidate heart sound.

FIG. **10** illustrates generally an example of portions of a method **1000** including calculating a cost for at least one candidate heart sound and recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the calculated cost. By calculating the cost of the at least one candidate heart sound, a desirable heart sound candidate for a particular heart sound waveform can be determined. In certain examples, the calculating the cost includes using a dynamic programming method, such as the Viterbi method or other dynamic programming method. In certain examples, the cost can be calculated using the cost analysis circuit **235**, and the first intra heart sound energy indication and the corresponding first intra heart sound time indication can be recognized using the heart sound recognition circuit **210**.

At **1005**, a cost can be calculated for the at least one second candidate heart sound. The calculating the cost can include at least one of calculating a jump penalty and calculating a local score. Calculating the jump penalty can include calculating a temporal cost associated with the at least one second candidate heart sound. In an example, calculating the jump penalty can include calculating the time difference between the second candidate heart sound and a first candidate heart sound. Typically, calculating the local score can include calculating a local benefit associated with the at least one second candidate heart sound. In an example, calculating the local score can include calculating the amplitude of the second candidate heart sound. In other examples, the calculating the jump penalty or the calculating the local score can include weighting the calculating to improve or optimize the cost calculation.

In an example, calculating the cost can include calculating a total score. Calculating the total score can include reducing a previous total score by the jump penalty, and then adding the local score to the maximum result of the reduced previous total score. (See, e.g., Eq. 1.)

At **1010**, the first intra heart sound energy indication and the corresponding first intra heart sound time indication can be recognized using the calculated cost. In an example, the recognizing the first intra heart sound energy indication and the corresponding first intra heart sound time indication can include recognizing the candidate heart sound having the least cost, or the maximum total score.

In other examples, once the first intra heart sound energy indication and the corresponding first intra heart sound time indication have been recognized, they can be stored, such as stored in a table, or stored in memory.

FIG. **11** illustrates generally an example of portions of a method **1100** including calculating a back pointer. In an example, the back pointer can be calculated using the heart sound recognition circuit **210**. At **1105**, a back pointer can be calculated. Generally, the back pointer can be indicative of the lowest cost path through multiple heart sound candidates of multiple heart sound waveforms.

In an example, the calculating the back pointer can include selecting the candidate heart sound having the maximum difference between the previous total score of the candidate heart sound and the current jump penalty. (See, e.g., Eq. 2.)

FIG. **12** illustrates generally an example of portions of a method **1200** including disregarding the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication and recapturing the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication. In certain examples, the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication can be disregarded using the coasting circuit **240**, and the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication can be recaptured using the recapture circuit **245**.

In certain examples, if the heart sound information from a particular heart sound waveform is different than the heart sound information from previous heart sound waveforms, then the different heart sound information can be disregarded, e.g., by skipping over the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication for that particular heart sound waveform. Similarly, if the heart sound information continues to be different, a buffered version of the disregarded recog-

nized first intra heart sound energy indication and corresponding disregarded recognized first intra heart sound time indication can be recaptured.

At **1205**, the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication can be disregarded. Generally, if the calculated cost of a recognized first intra heart sound energy indication and corresponding first intra heart sound time indication is too high (e.g., above a threshold, or above previous results), or if the total score of the recognized first intra heart sound energy indication and corresponding first intra heart sound time indication is too low (e.g., below a threshold, or below previous results), then the recognized first intra heart sound energy indication and corresponding first intra heart sound time indication can be disregarded.

In an example, the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication can be disregarded for a certain period (e.g., a certain number of heart sound waveforms, a certain period of time, etc.). In an example, if, at the end of the certain period, the calculated cost remains too high, or if the total score remains too low, the disregarding can cease. This can be indicative of a change (e.g., physical change, physiological change, system failure, environmental change, etc.). In an example, once it is determined that the heart sound information is relatively consistent (e.g., after disregarding for the certain period), the information should no longer be disregarded.

In an example, the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication can be disregarded, with the disregarding triggered using a comparison. The using the comparison can include using a comparison of the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

At **1210**, the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication can be recaptured. In an example, if the disregarding occurs for the certain period, then it may be beneficial to recapture the disregarded recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication (e.g., it may be beneficial if the heart sound information has changed, if the subject's status has changed, etc.). In an example, if the disregarding occurs for a period shorter than the certain period (e.g., the heart sound information is different for only a short time, such as one heart sound waveform), then it may not be beneficial to recapture the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication (e.g., the disregarded information can consist of noise or useless data).

In an example, the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication can be recaptured, with the recapturing triggered using a comparison. The comparison can include a comparison of the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication and at least one other recognized intra heart sound energy indication and a corresponding at least one other recognized intra heart sound time indication within the particular heart sound of at least one other heart sound waveform.

FIG. **13** illustrates generally an example of a system **1300** including an implantable medical device **215**, an input circuit **205**, and a heart sound recognition circuit **210**. The implantable medical device **215** can include a heart sound sensor **220** and a heart sound feature detector **225**. In certain examples, the implantable medical device **215** can include an implantable cardiac rhythm management (CRM) device, such as a pacer, defibrillator, cardiac resynchronization therapy (CRT) or other such CRM device. In this example, the implantable medical device **215** is implanted in a subject **201**. Generally, the heart sound sensor **220** can be configured to sense a heart sound signal of the subject **201**. The heart sound feature detector **225** is coupled to the heart sound sensor **220** and can be configured to receive the heart sound signal from the heart sound sensor **220**. In an example, the heart sound feature detector **225** can be configured to detect at least one feature of at least a portion of at least one heart sound.

In an example, the input circuit **205** can be communicatively coupled to the implantable medical device **215**, and can be configured to receive heart sound information from the heart sound sensor **220**, or at least one heart sound feature from the heart sound feature detector **225**. In an example, the heart sound recognition circuit **210** is coupled to the input circuit **205**, and can be configured to receive heart sound information from the input circuit **205**. Generally, the heart sound recognition circuit **210** can be configured to recognize, within a particular heart sound of a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication using the heart sound information from the particular heart sound waveform and the heart sound information from at least one other heart sound waveform.

The recognized first intra heart sound energy indication and the corresponding recognized first heart sound time indication can be used to detect heart failure (HF) decompensation. In an example, an improved S3 amplitude and timing recognition can provide earlier HF decompensation detection than other HF decompensation detection methods (e.g., thoracic impedance HF decompensation detection).

In the examples of FIG. **1-13**, various examples, including receiving heart sound information, recognizing a first intra heart sound energy indication and a corresponding first intra heart sound time indication, implantable sensing a heart sound signal, implantable detecting at least one heart sound feature, detecting at least one heart sound candidate, calculating a cost for the at least one heart sound candidate, calculating a back pointer, disregarding the recognized first intra heart sound energy indication and the corresponding recognized first intra heart sound time indication, or recapturing the disregarded recognized first intra heart sound energy indication and the corresponding disregarded recognized first intra heart sound time indication, are disclosed. It is to be understood that these examples are not exclusive, and can be implemented either alone or in combination, or in various permutations or combinations.

It is to be understood that the above description is intended to be illustrative, and not restrictive. For example, the above-described embodiments (and/or aspects thereof) may be used in combination with each other. Many other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including"

and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.

The Abstract is provided to comply with 37 C.F.R. §1.72 (b), which requires that it allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description, with each claim standing on its own as a separate embodiment.

What is claimed is:

1. A system, comprising:

an input circuit configured to receive heart sound information; and

a heart sound recognition circuit, coupled to the input circuit, the heart sound recognition circuit configured to recognize, within a particular heart sound of a particular heart sound type, and within a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication using the heart sound information from the particular heart sound waveform and heart sound information from at least one other heart sound waveform;

a detection circuit configured to identify a candidate heart sound for the particular heart sound of the particular heart sound type using the heart sound information from the particular heart sound waveform or from the at least one other heart sound waveform; and

a cost analysis circuit configured to calculate a cost for the candidate heart sound, the cost including a jump penalty indicative of a temporal cost associated with the candidate heart sound;

wherein the heart sound recognition circuit is configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the cost.

2. The system of claim **1**, wherein the particular heart sound of the particular heart sound type includes at least a portion of one of S1, S2, S3, and S4; and

wherein the first intra heart sound energy indication and the corresponding first intra heart sound time indication corresponds to the at least a portion of one of S1, S2, S3, and S4, respectively.

3. The system of claim **1**, wherein the cost includes a local score indicative of a local benefit associated with the candidate heart sound.

4. The system of claim **1**, wherein the heart sound recognition circuit is configured to determine a back pointer indicative of a pointer from the candidate heart sound to an optimal candidate heart sound using the cost.

5. The system of claim **1**, wherein the particular heart sound of the particular heart sound type, and within the particular heart sound waveform includes an ensemble averaged heart sound over multiple physiological cycles.

6. A system, comprising:

an input circuit configured to receive heart sound information; and

a heart sound recognition circuit, coupled to the input circuit, the heart sound recognition circuit configured to recognize, within a particular heart sound of a particular heart sound type, and within a particular heart sound waveform, a first intra heart sound energy indication and a corresponding first intra heart sound time indication using the heart sound information from the particular heart sound waveform and heart sound information from at least one other heart sound waveform;

wherein the particular heart sound of the particular heart sound type includes at least a portion of one of S1, S2, S3, and S4;

wherein the first intra heart sound energy indication and the corresponding first intra heart sound time indication corresponds to the at least a portion of one of S1, S2, S3, and S4, respectively;

wherein the heart sound recognition circuit includes a detection circuit configured to detect a first candidate heart sound for the particular heart sound of the particular heart sound type using the heart sound information from the particular heart sound waveform and to detect a second candidate heart sound for the particular heart sound of the particular heart sound type using the heart sound information from the at least one other heart sound waveform; and

wherein the heart sound recognition circuit is configured to recognize the first intra heart sound energy indication and the corresponding first intra heart sound time indication using the first candidate heart sound and the second candidate heart sound.

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